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Rectification of Alternating Currents by Means of a Carbon Arc

Electrical Engineering

B. S.

1912

RECTIFICATION OF ALTERNATING CURRENTS BY MEANS OF A CARBON ARC

BY

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THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1912

UNIVERSITY OF ILLINOIS

May 28, 1902

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

ARCHIBALD BEEBE VAN DEUSEN

ENTITLED RECTIFICATION OF ALTERNATING CURRENTS

BY MEANS OF A CARBON ARC

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

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I

Introduction

The rectification of alternating current, that is the transformation from alternating to direct current, has become an important problem to electrical engineers. Alternating current is preferable for transmission on account of its easy voltage transformation which allows the use of high voltages and the consequent saving in line copper. Direct current is desirable for variable speed motors and some forms of lighting. It is also desirable to have but one type of generator, alternating or direct, in a power station for economy of floor space and efficiency of operation. Hence some means of transformation from alternating to direct current is necessary, especially at the end of a transmission line. This rectification is now accomplished by means of synchronous converters which are built in large sizes, rectifying large amounts of power. These machines have large rotating parts, being much like a combined motor generator and demand constant and experienced attention. Another rectifier which may be used for small amounts of power, such as charging automobiles, is the mercury vapor rectifier. This type employs a vacuum tube which

is very fragile. It is thus desirable that another rectifier be found which will be durable, and which may be used for large amounts of power without great operating difficulties. For this reason a preliminary investigation into the possibilities of rectification by means of a carbon arc arc is taken up in this thesis.

II

Fundamental Ideas.

The idea or theory of the unidirectional conductor is fundamental in rectification with the carbon arc. Alternating current is a fairly well-known phenomena. It is a series of electric impulses. The electromotive force starting at zero rises to a positive maximum, falls to zero,

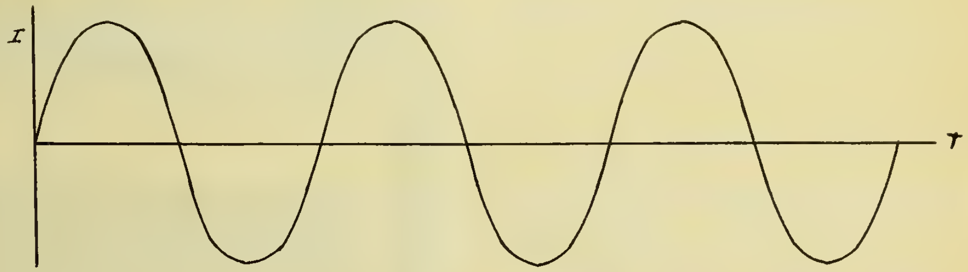

Fig. 1.

Sine wave of current.

rises to a negative maximum, and again falls to zero, thus completing one cycle, which is then repeated. The current in like manner starts from zero, rises to a maximum in one direction, falls to zero, rises to a maximum in the other direction, and again falls to zero, completing the cycle which is then repeated. This rise and fall generally follow some definite law and hence may be either mathematically or graphically represented. The

most common law is the sine curve which for a current has the following equation:

$$i = I \text{ sine } \omega t$$

where i is the instantaneous current, large I denotes its maximum value, and t denotes time. This law is graphically represented in Fig. 1. The curve is symmetrical with respect to the t axis, that part of the curve above the axis represents current in one direction, that below the axis in the reverse. If now it were possible to divide this current so that only that part which is in one direction (that part on one side of the axis) would be effective in a circuit, we would have a current as shown in Fig. 2, consisting of a series of impulses in one direction. This would be a pulsating direct current, and providing these impulses could be obtained frequently enough it could be used as direct current.

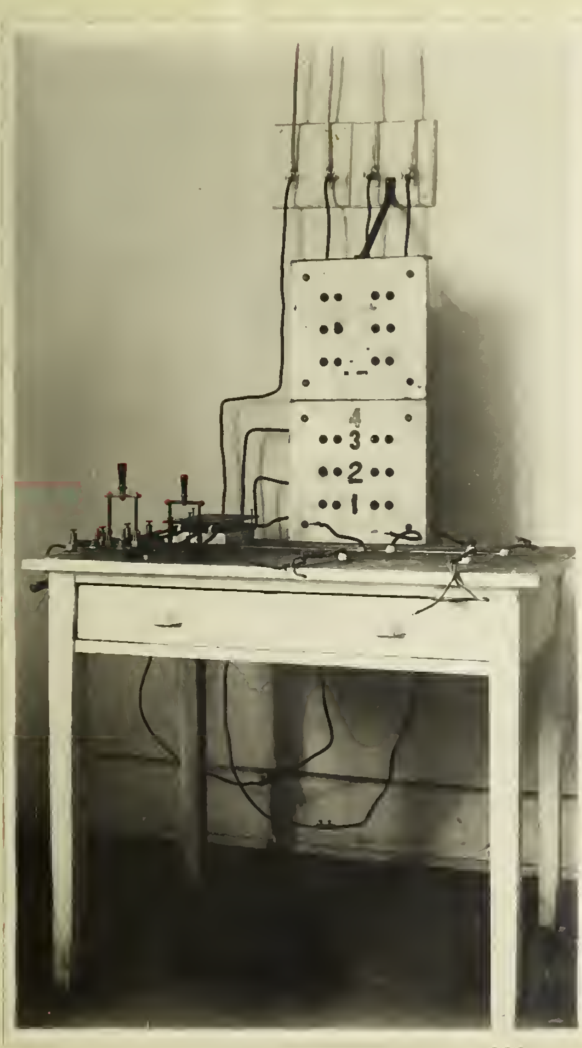

Plate 1.
Instrument Table and Plug-board for Facility in Making Connections.

Most conductors such as copper, iron, etc., will allow electric current to flow through them in either direction. Several conductors, however, have been found which will allow current to flow through them in one direction but not in the opposite direction. The mercury

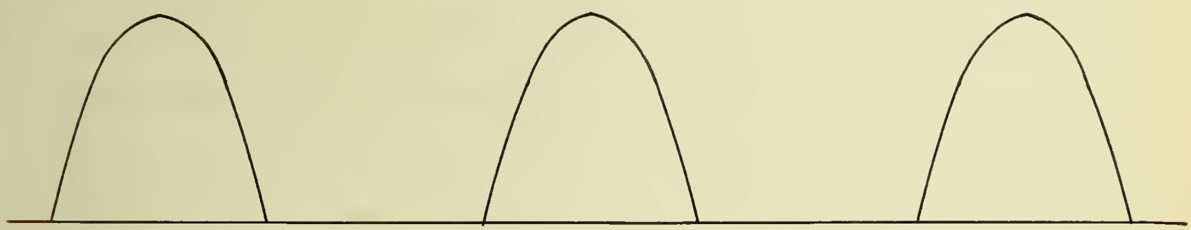

Fig. 2.

Theoretical rectified sine wave sought.

vapor arc, and several chemical electrolytes have this property, and hence are called unidirectional conductors, because they will only conduct electricity in one direction. The exact reason for this unidirectional conductive property has not been fully investigated. It is, however, probably due to the flow of ions which make up the conductor. As far as this thesis is concerned, the mere fact is sufficient, without any scientific explanation. If now such a conductor is included in an alternating current circuit, only that part of the current or impulse which is in one direction will be able to flow, that which is in the opposite direction will not be able to flow in the circuit but will be suppressed, and such a wave of current as shown in Fig. 2 will be obtained.

III

References.

Mrs. Aryton in her work, "The Electric Arc", page 70, mentions the fact that the carbon arc is a uni-directional conductor. Fig. 3 shows the appartus by means of which she came to this conclusion. The diagram is self-explanatory. A and B are the carbons of a direct current arc, E is a small third or auxiliary carbon immerged in the arc stream. If now the connections are made ac and bd, the galvanometer gave a deflection. The

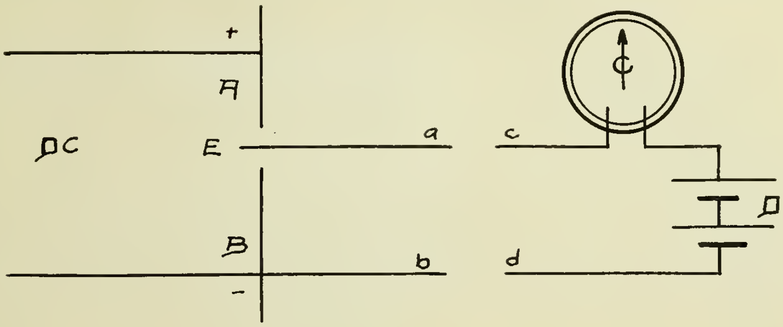

Fig. 3.

Diagram of Aryton's experiment to show unidirectional nature of D C carbon arc.

galvanometer circuit now includes the portion of the D C arc between B and E. If however the connections are made, ad and bc, no deflection was noticed. From this Mrs. Aryton concluded that the direct current arc would conduct electricity in one direction only.

Dr. Steinmetz in his book, " Radiation, Light, and Illumination", page 113, arrives at this same conclusion, but in a slightly different way. The appartus he used is shown diagramatically in Fig. 4. It consists of a simple

carbon arc which is started by touching the carbons A and C together (See Fig. 4.) The voltage betw en A and C is evidently,

$$e = E - i (R_1 + R_2)$$

while that between B and C is

$$e_1 = E - iR_2$$

hence

$$e_1 - e = iR_1$$

or B is more negative than A by the amount iR_1. It would be expected that some current would flow in B. The cathode

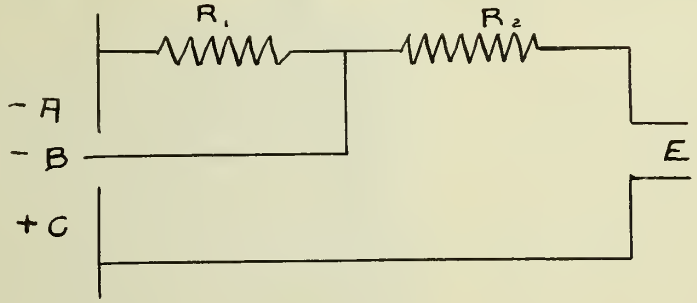

Fig. 4.

Diagram of Steinmetz' apparatus to show unidirectional nature of D C carbon arc.

spot is on A. And since B does not touch A to receive this spot no current will flow to C to B as Dr. Steinmetz proves in this same volume, pages 111 and 112. B however, is more negative than A and hence would act as a cathode to A, and current might flow from A to B. This, however, was not the case, as no current could be detected in B. The polarity of the circuit was now reversed, making A and B positive and C negative. This makes B more positive than A, or A is now the cathode in respect to B. The tendency is now for current to flow from B to A, and this was the case, there being a

current in B. Dr. Steinmetz therefore concluded that a D C carbon arc was a unidirectional conductor; for in the first case the current tended to flow against the arc stream and could not, while in the second case it tended to flow with the arc stream, which it did. In view of this conclusion, Dr. Steinmetz went further and suggested rectification with the carbon arc, making use of its unidirectional conducting nature.

Plate 2
The Arc Showing Curtains and Ruby Screen for Protecting Operator's Eyes.

IV

Rectification With Carbon Third Terminal.

Fig. 5 is the diagram of the apparatus used in this thesis. This is the method suggested by Dr. Steinmetz in his book, "Radiation, Light, and Illunination", page 114. A portion (A C) of a direct current carbon arc (A B) is included in an alternating current circuit. On account of the unidirectional conductive property of the arc, only that half of the alternating current which is in one direction can flow in the A C

circuit. Thus a pulsating direct current is obtained as previously stated. The load on the rectified circuit is 16, 32 candle power lamps, all the meters used indicate direct current only.

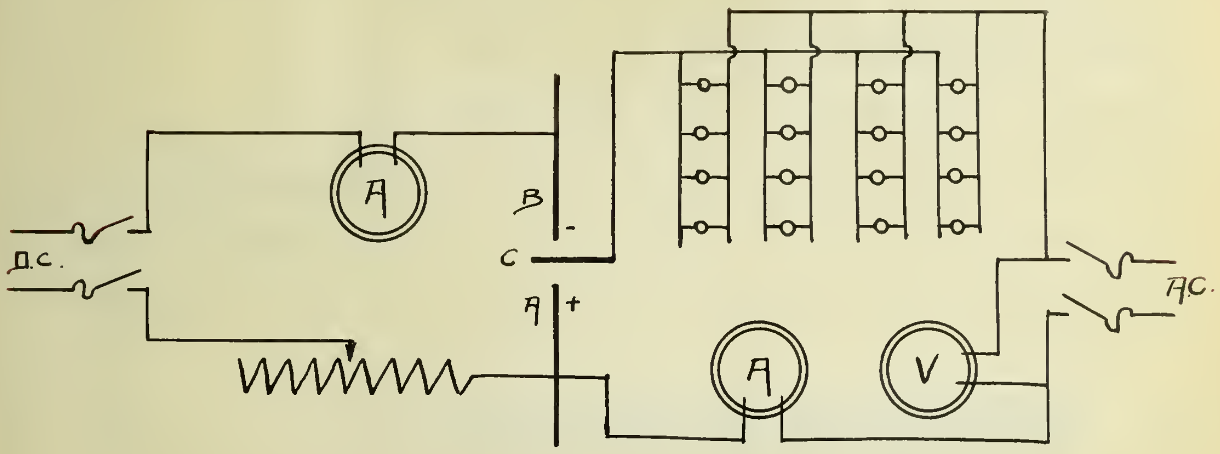

Fig. 5.

Diagram of Rectifying Apparatus.

Actual rectification was attempted with the apparatus as shown in Fig. 5. After many trials it was decided that the longest and steadiest D C arc could be obtained by using two Electra flame carbons, at A and B, each being about half an inch in diameter. It was necessary to have sufficient space between A and B to insert C and have an appreciable gap between C and both A and B. This necessitated at least a half and preferably three quarters of an inch between A and B. Thus the D C arc had to be about three quarters of an inch long. At first 110 volts D C was used but it soon became evident that this was too low, and that not enough voltage could be absorbed in the resistance to have the proper steadying effect. The arc went out on the least provocation. The introduction of the

cold third terminal, with the attended air disturbances being sufficient to do this. After many trials it was found best to have the arc stream ascending, the positive carbon being below and the negative above. The voltage rectified was 110 volts A C. Using 110 volts D C the maximum length of time of rectification was about five minutes, which was not sufficient for a proper investigation of the phenomena. To overcome this difficulty, 220 volts D C was used, and then the time of continuous rectification was limited only

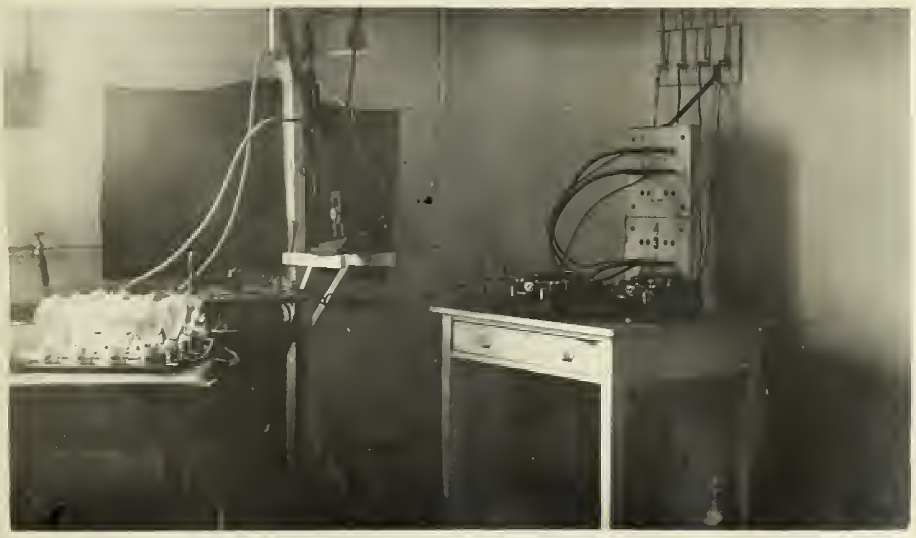

Plate 3.

The Apparatus Connected for Rectification.

by the burning away of the carbons, which was rapid as the arc was not enclosed.

Early in the investigations it was evident that the position of the third or auxiliary carbon in the arc stream was of prime importance. When this carbon was in the edge of the arc stream, the load lamps glowed at about one quarter candle power, the D C ammeter and voltmeter in the load

circuit indicated low values, and a loud snapping noise came from the arc accompanied by minute flashes of light on the third terminal, which remained black and apparently cool or nearly so. If, however, the carbon was placed in the center or core of the stream, the above phenomena though at first apparent, were quickly replaced by a hum similar to that of the A C arc, the carbon became hot, having a bright spot similar to the cathode spot wandering about its tip. The lights also came up to full candle power, and the meter readings were decidedly increased. These meter readings, however, did not seem right. The meters giving an indication was evidence of the fact that rectification was taking place. They only showed, however, about 30 volts and 4. 5 amperes. To obtain this same illumination with ordinary direct current, 110 volts and 16 amperes would be necessary. This showed that some un-

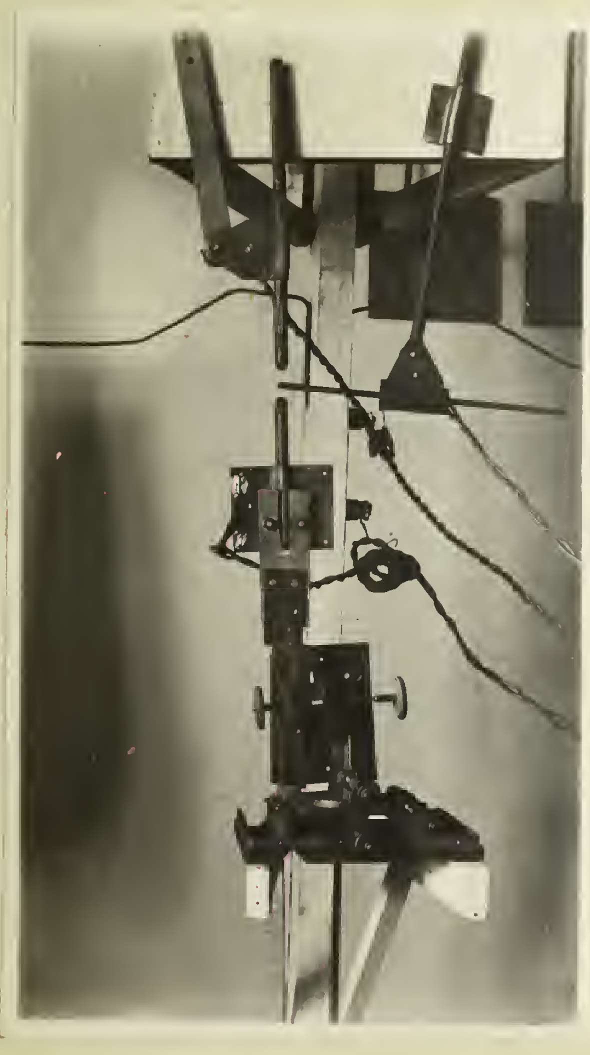

Plate 4.

The Arc Showing Arrangement and Adjustment of the Three Carbons.

known phenomena was taking place in the circuit.

To further test the nature of the rectified curremt a direct current arc lamp was substituted for the incandensent lamps. This absolutely refused to operate on the rectified current. It was further noted that the incandescent lamps often burned brightly for a short time after the D C sustaining arc went out, and that there was apparently

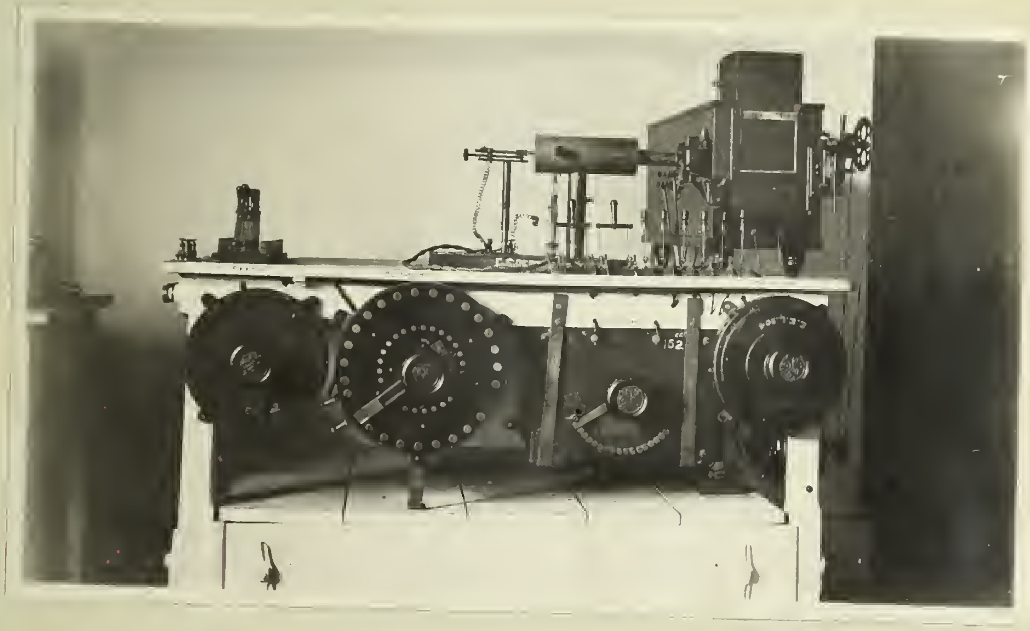

Plate 5.

The Oscillograph.

an arc between A and C (See Fig. 5.) For these reasons it was decided to study the nature of the rectified current by menns of the oscillograph.

The oscillograph at once gave the true explanation of the above mentioned phenomena. In taking the following oscillograms the rectifying apparatus was as per Fig. 5, 220 volts were impressed on the arc, and the carbon was used for the third terminal which was placed in the core of the

Fig.6.

Current wave obtained with auxiliary carbon terminal showing incomplete rectification.

Fig.7.

Voltage wave obtained with auxiliary carbon terminal showing incomplete rectification.

arc stream. An oscillogram of the current in the load is shown in Fig. 6, and a similar voltage curve is shown in Fig.7. These oscillograms show that only partial rectification has taken place. Due to the unidirectional conductive properties of the D C arc, the current in one direction could flow easily, which is shown by the large loop above the ground line (Fig. 6.). In order to flow in the opposite direction the alternating current had to establish an arc of its own between A and C (See Fig. 5.) which it could do as the carbon C was hot. The current of this arc was however opposed by the D C arc and hence only a small amount was able to flow, giving a small loop below the ground line (Fig. 6.) . The resultant current was partially alternating and partially direct. The same discussion holds true for the voltage wave. This gave a very satisfactory explanation of the apparently contradictory phenomena previously observed. The incandescent lamps derived their brilliancy from the compound wave, while the D C meters only indicated the direct current part of it. The arc lamp could not operate on account of the presence of the alternating current, and the arc observed between A and C (Fig. 5.) was actually an A C arc which gave the humming noise already mentioned.

The third carbon was now placed on the edge of the arc stream and this condition was investigated by means of the oscillograph, all else remaining as indicated in the preceeding paragraph. The third carbon was black, apparently cool, and minute flashes light appeared upon it accompanied by a loud snapping sound. Very interesting results were

Fig.8.

Current wave obtained with auxiliary carbon terminal showing partially complete rectification.

Fig. 9.

Current wave obtained with auxiliary carbon terminal showing incomplete rectification.

obtained as shown in Figs. 8 and 9. These two oscillograms are of current waves and are excellent examples of waves observed under these conditions. It was concluded that total rectification was possible, indications of which are to be found at A and B Fig. 8. This total rectification was next sought, by varying the position of the third terminal. It was obtained by many trials as shown by Figs. 10 and 11 which are oscillograms of voltage and current waves respectively. Fig. 12 is an oscillogram of both

Fig. 10.
Voltage wave obtained with auxiliary carbon terminal showing almost complete rectification.

current and voltage in the rectifying circuit. This figure shows that the waves hold nearly the same shape and are in phase. The reason for this large or total rectification is

Fig. 11.

Current wave obtained by auxiliary carbon terminal showing almost complete rectification.

Fig. 12.

Current and voltage wave obtained with auxiliary carbon terminal showing relation in phase and shape.

evident. The third carbon being partially out of the arc stream remains cool, and hence there is great opposition to the starting of the A C arc, which wholly or partially eliminates the alternating current apparent in a small loop of the curves previously mentioned, giving total rectification. It is to be noted here that all these waves are semi-transient phenomena, the wave shape varying considerably in a few cycles. The oscillograms shown in Figs. 6 and 7 were easily taken for the condition prevailing then was a fairly permanent one. In obtaining the oscillograms shown in Figs. 8-12, other methods were necessary as this condition, as denoted by the snapping sound , was only momentary. Everything being in readiness the third terminal was placed near the edge of the arc stream. The oscillogram was taken when the snapping noise was heard, brought about by the shifting of the arc, or the burning away of the third carbon. As this condition was only momentary it is concluded, that to obtain total rectification it would be necessary to have an enclosed D C arc easily adjusted, and that the third terminal or auxiliary carbon would need a very delicate automatic adjustment. Thus such rectification would present great difficulties.

V

Rectification with Cool Third Terminal.

It is a well known fact that an electric arc cannot be established and held between two cold terminals. It has been noted that the most complete rectification was obtained when the third carbon terminal was cold. It was concluded

that if this terminal could be kept cold the A C arc would not be able to start and complete rectification would result. This forms the basis for the next set of experiments. A thin copper tube was substituted for this auxiliary carbon, as the third terminal, and cooling water was kept running through it. This kept the tube thoroughly cooled during the following experiments. The circuits were unchanged, being as per Fig. 5, with C the cooled tube.

Plate 6

The Arc Showing Arrangement And Adjustment of Cool Terminal.

It was found that the position of this tube in the arc stream was not of as great importance as for the carbon. It was placed in the center or core of the D C arc and behaved much as the carbon when in the edge of the stream.

The loud snapping noise was again heard, points or flashes of light were observed on the tube, and the lamps of the load burn considerably below full candle power. When further investigated with the oscillograph the results

Fig. 13.

Current wave obtained with cooled auxiliary terminal showing complete rectification.

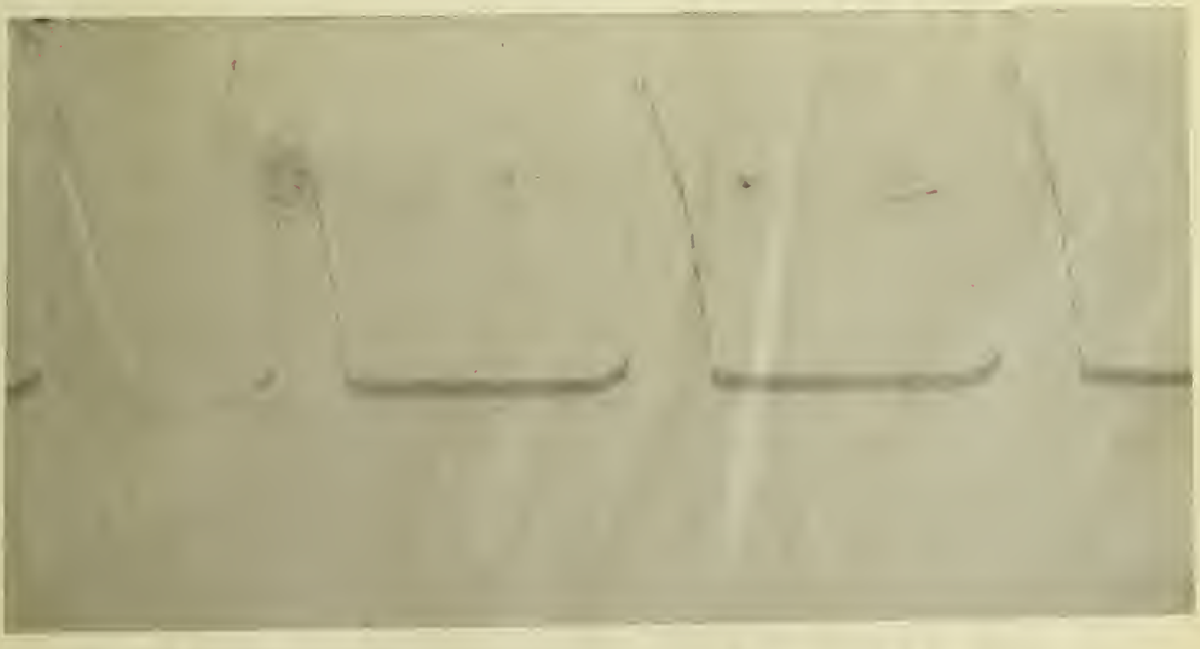

Fig. 14.

Current wave obtained with cooled auxiliary terminal showing complete rectification.

were most satisfactory. Figs. 13 and 14 are two oscillograms of the current in the load showing total rectification. The alternating part of the wave, which is partly apparent below the ground line in Fig. 6, has been entirely suppressed. Fig. 15 is an oscillogram of voltage which is also very satisfactory showing complete rectification. Both current and voltage waves are shown in the oscillogram Fig. 16. It is evident that they follow each other closely and are in phase.

These oscillograms show that the waves of both voltage and current are very narrow in comparison with the space between them. This is accounted for as follows. When the alternating or rectified current commences to flow it must first overcome the voltage of the rectifying D C arc. Thus the value of the rectified voltage is

$$(1) \quad e_1 = \frac{\sqrt{2}}{\pi} e_2 - K$$

(From Steinmetz' "Transient Electric Phenomena and Oscillations," page 252.)

Here e_1 is the rectified voltage, e_2 the effective value of the A C voltage before rectification, and K is a constant, being the voltage of the D C arc between the A C terminals (See A C Fig. 5.) Thus we must substract a constant from the instantaneous values of the rectified wave. The wave before rectification appears as a full line in Fig. 17. A constant is now subtracted from each loop and if the alternating wave continues, the wave as shown by the dotted line in Fig. 17 will result. One half, however, is suppressed in rectifying and the result is a wave as shown in Fig. 18. This

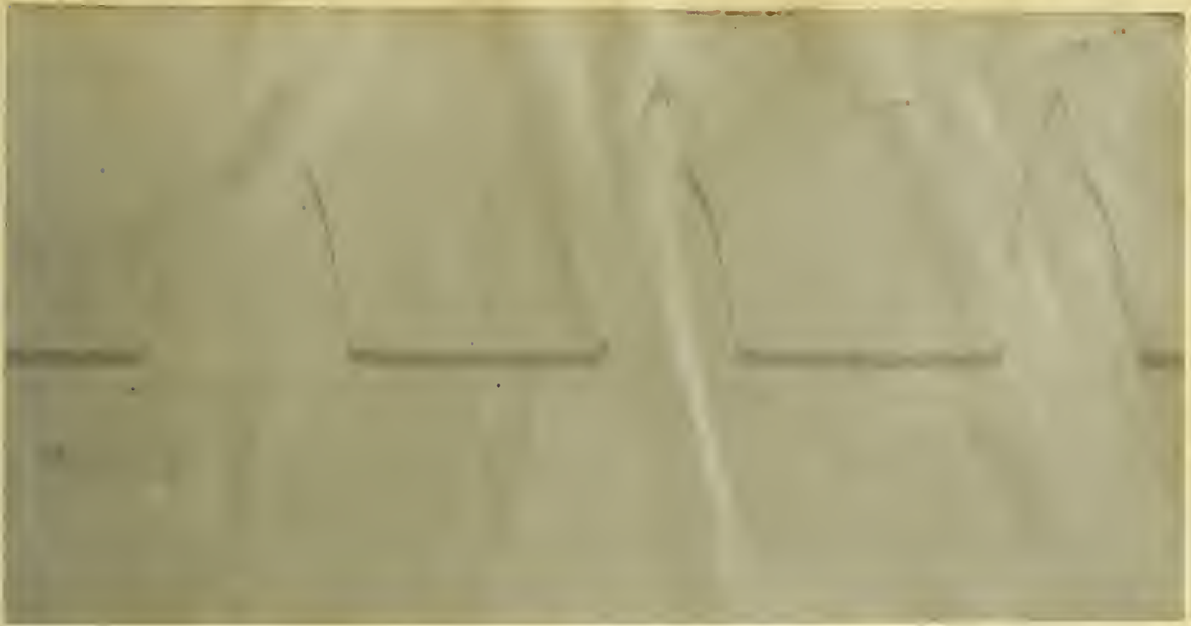

Fig. 15.

Voltage wave obtained with the cooled terminals showing complete rectification.

Fig. 16.

Voltage and current wave obtained with cooled terminals showing shape and phase relation.

demonstrates very clearly why the space between the loops in Figs. 13-16 is greater than the width of the loop or wave itself.

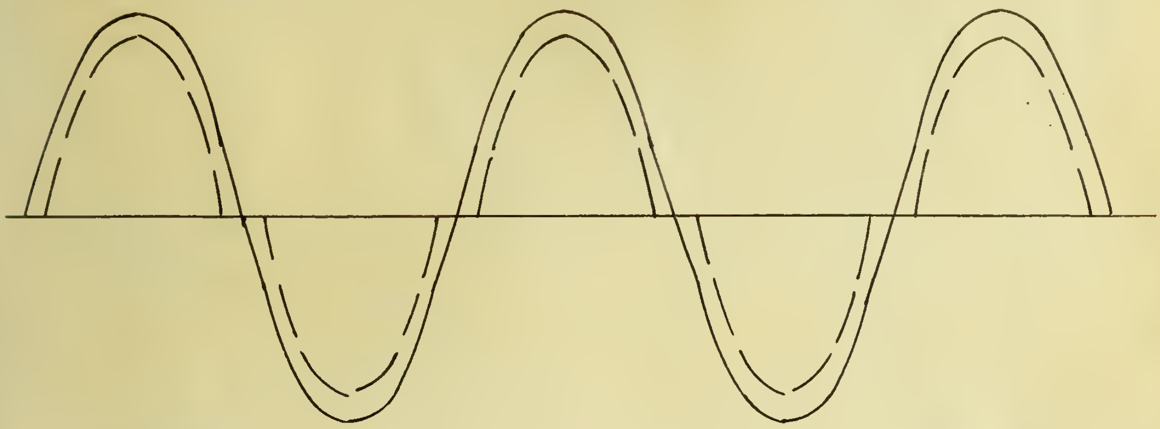

Fig. 17.

It was experimentally determined that either part of the A C wave could be obtained, giving a pulsating direct current in either direction. This was accomplished by leaving one terminal of the A C circuit on C (See Fig. 5.), while the other was on A or B. If A was used the rectified current was in one direction, if B was used this current was in the opposite direction.

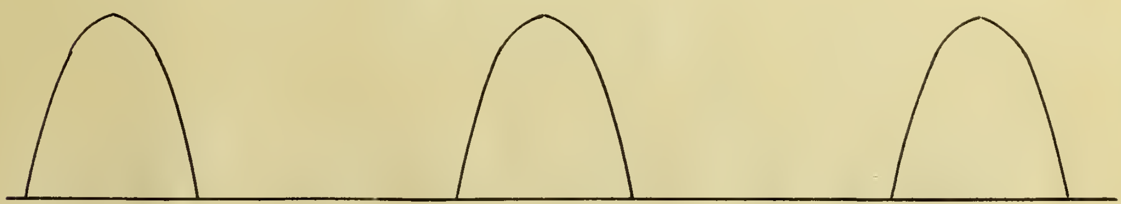

Fig. 18.

No attempt was made to callibrate these oscillograms. The current was variable,depending upon the lights and the load, hence callibration was not necessary. Callibration of the voltage wave would have a definite meaning. From (1) it is evident that the value of the rectified voltage is considerably less than half the value of the same voltage unrectified. A rough attempt at the callibration of the voltage oscillograms showed this to be the case. Concerning the duration of continuous rectification with the cool third terminal no definite attempts were made. Rectification, once started, continued for a considerable period of time, long enough for two oscillograms to be taken. It was then stopped by opening the switches. It is concluded that continuous rectification could be obtained until the D C carbons had burned away sufficiently to extinguish the arc. Thus, if this arc could be maintained enclosed, both upper and lower carbons being adjusted, rectification could continue indefinitely.

VI

Conclusion.

No definite statements can as yet be made concerning the efficiency of this method of rectification. It is evident than less than half the A C input is used, and there is a large power consumption in the D C arc and steading resistance. Twenty percent is the estimated efficiency. The efficiency or yet commercial possibility, however, is not the object of this paper. These experiments are among the first in this method of rectification and quality, not quan-

tity is the object, together with the knowledge of the fundamental principles involved.

In conclusion, it is evident that this scheme of rectification, using the cool third terminal is possible. The rectification of alternating to direct current has been accomplished. This direct current has a decidedly pulsating nature, and that so far obtained could not be used as direct current for all purposes. The further soltution of the problem contains a difficult mechanical side, including the construction of a self-regulating D C arc and a self-adjusting cooled third terminal. It also presents a difficult theoretical side from the electrical standpoint. This includes obtaining the impulses nearer together and some manner of using the other half of the A C wave which has so far been suppressed, together with a mathematical solution of the phenomena present. Thus in this paper only the basic principles of rectification of alternating current by means of the carbon arc are set forth.